*March 2010*

*Hunter College*

# 100 Years of Cosmology: From Spiral Nebulae to the CMB

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*NASA/GISS & NASA/Ames*

*http://astrophysics.arc.nasa.gov/~mway/Hunter.pdf*

Planck: “A new scientific truth doesn’t triumph by convincing its opponents of that truth, but because they eventually die & a new generation grows up that is familiar with that truth”

# Galaxy Cosmology? 900-1900

964 Al-Sufi: Records observation of The Andromeda Nebula/M31

1546-1601 Tycho Brahe

1610 Galileo: Milky Way composed of innumerable fixed stars

1612 Simon Marius von Guntzenhausen: Observes Andromeda (cloudy)

1664 Ishmael Boulliau: Sees Andromeda when looking for comet

1667 – Again, now with findings of Marius & Al-Sufi/Anonymous?

1690 John Hevelius: Mentions Marius observations of Andromeda (last catalog to be compiled from naked-eye observations alone)

1745 Pierre de Maupertuis: Nebular stars, dense crowds of stars

1749 Le Gentil: M32, De La Caille, Oriani, Koehler, Bode, Messier

1750 Thomas Wright: Milky Way is flattened

1750 John Bevis: First catalog with LMC/SMC? Mentioned in 1515..

1755 Immanuel Kant: speculates that elliptical stars of Maupertuis are galaxies (**island universes**)

1796: Pierre-Simon Laplace: 'Exposition of a World System'

1868 William Huggins: first stellar doppler shift measured

# Part I

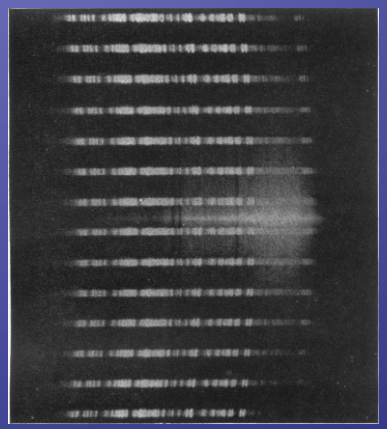
# What is the size & nature of Our Universe?

# 1912: Vesto Melvin Slipher

First to discover a large spectral shift for a spiral nebula (blue shift in fact)

- From Lowell Observatory's 24" telescope
  - 6h50m exposure time (September 17, 1912)
  - First stellar Doppler shift was 1868 (Huggins)
- Was traveling at an incredible −300 km/s

Isaac Roberts (1899) 20" reflector



Pease (1918)

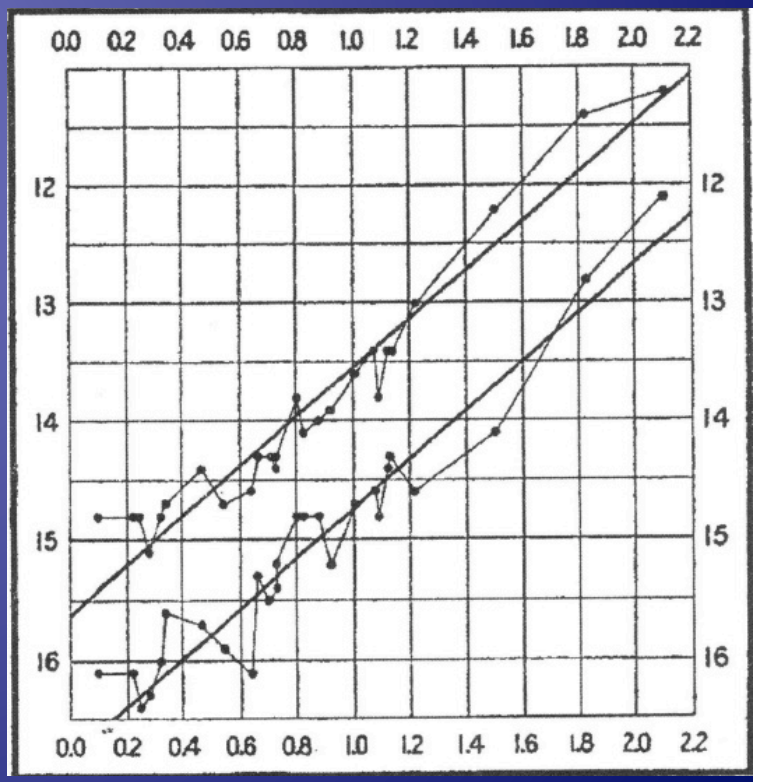
# 1912: Henrietta Swan Leavitt

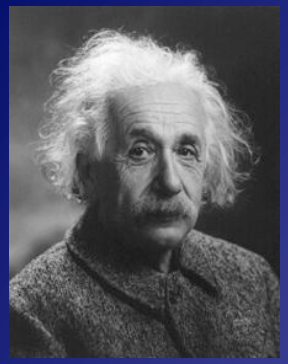
Publishes a period-luminosity relationship for Cepheid variables in Magellanic Clouds

1918: The First Cepheid **distance** is actually estimated

A good way to get get distances to distant objects in the Universe

SMC





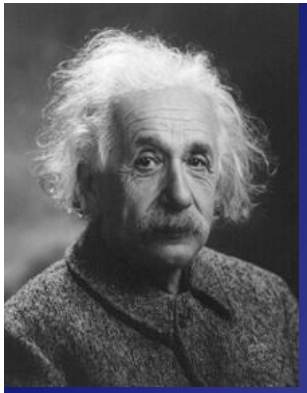
# Albert Einstein: 1915 -17

Develops the theory of General Relativity

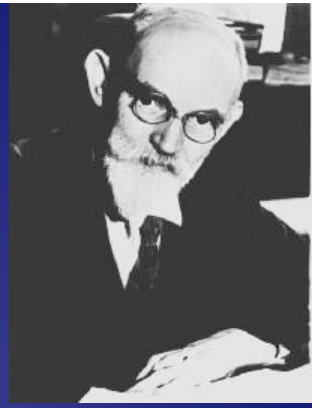
$$G_{ab} + \Lambda g_{ab} = kT_{ab}$$

Provides the theoretical framework for the development of cosmological models

Recall that $\Lambda$ came in 1917 (Steady-State). It will disappear later and return again…



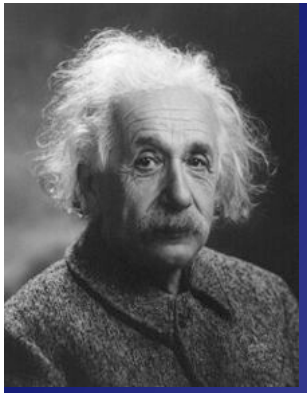
# Einstein & de Sitter: 1917



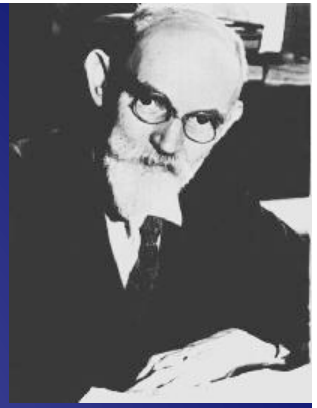
Two cosmological models (solutions) arise:

A.) Einstein's static matter filled world

- Homogeneously filled with dilute matter
- Contained a definite mass
- In equilibrium, no internal pressures or stresses



# Einstein & de Sitter: 1917



B.) Willem de Sitter's static empty model

- Predicted "spurious positive radial velocities" for distant objects
- They were not regarded as coming from the expansion of space (**still** a "static" model)

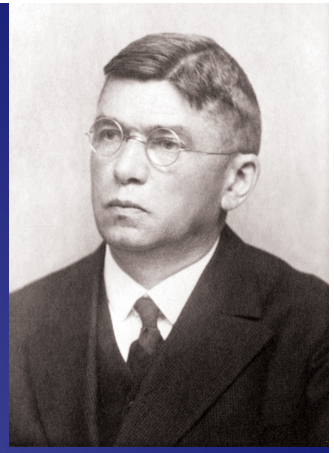
# 1917: Vesto Melvin Slipher

- 1917: Reported radial velocities of nearly 25 nebulae (21 redshifted)
  - Four had velocities greater than 1000 km/s
- No mention of these being interpreted in terms of Einstein's or de Sitter's universe
  - Recurring theme: Observers/Theorists
  - 1925: reported 45 nebulae (41 redshifted)

Is there a relation amongst these nebulae of large velocities?

Magnitudes vs Velocities?
Distance vs Velocities?

# 1918/21: Carl Wilhelm Wirtz



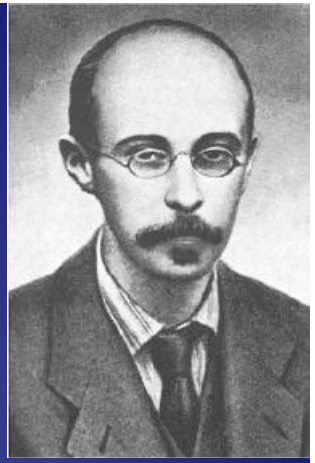
- One of the first to estimate nebular motion a whole using a decent sample
  - 16 nebular radial velocities via Paddoc (1916)
  - $v=X\cos\alpha\cos\delta+Y\sin\alpha\cos\delta+Z\sin\delta+K$ (Airy)
  - $v_{solar}$=-831 km/s , $K_{nebulae}$=+656 km/s
- 1918: "*If one gives this value* a literal interpretation, the system of spiral nebulae disperses with the velocity 656 km/s relative to the momentary position of the solar system as center."
- 1921: Describes a **linear relationship between nebular magnitudes (distance) and velocities** in an unpublished diagram **linking it to the de Sitter effect**.
- An Observer who knows his theory?!

# Early Dating of Earth's Age

- 1921: H.N. Russell: $4 \times 10^9$ yrs is max age of Earth's crust via radioactive dating of Thorium & Uranium
- 1929: Rutherford: $3.4 \times 10^9$ yrs via U-235 and U-238
- 1930s: $2\text{-}3 \times 10^9$ yrs is accepted age of Earth using radioactive dating techniques

# More Solutions to Einstein's General Relativity Equations Arise in the 1920s…

# Alexander Friedman (1922)



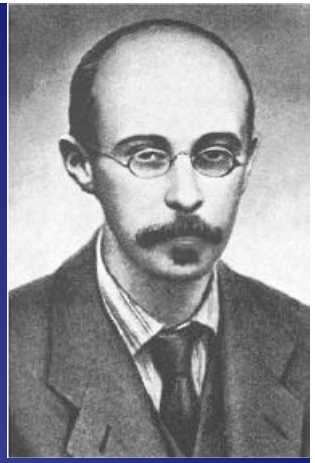
1888-1925

- Additional solutions to Einstein's GR eqns
  (Including a non-static matter-filled **world** model)

- 1922 ZS f. Phys. 10, 377 [1999 Gen. Rel. Grav. 31, 1991]
  - General Relativity allows a "closed" universe with a time-dependent radius

- 1924 ZS f. Phys. 21, 326 [1999 Gen. Rel. Grav. 31, 2001]
  - GR equations also allow an "open" hyperbolic (negative curvature) universe

# Alexander Friedman (1922)

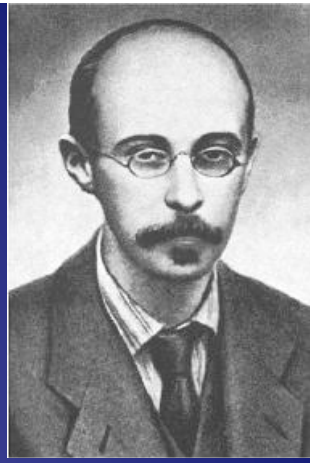


1888-1925

- 1922 Paper: "The purpose of this note is to show that the Einstein and de Sitter worlds are special cases of more general assumptions, and to demonstrate the possibility of a world in which the curvature of space is constant with respect to the 3 spatial coordinates but **does** depend on time R=R(t). This new type is an analogue of the Einstein world model."

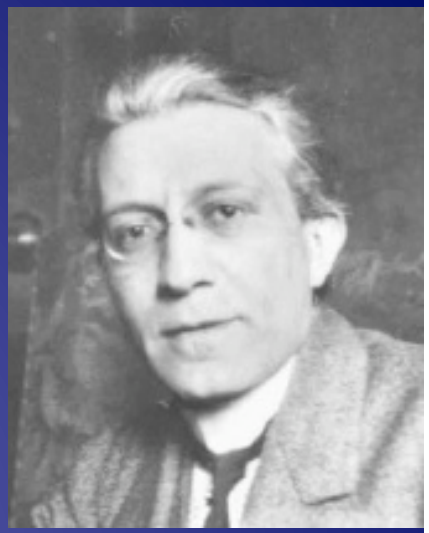
- For illustration he set $\Lambda=0$ and $M=5\times10^{21}M_{sun}$ giving a world model age of about $10^{10}$ yrs:

# Alexander Friedman (1922)



- BUT he is honest…
- “our knowledge is completely insufficient for a numerical comparison to decide which world is ours”
- The papers are of a purely mathematical nature
- There was NO attempt to incorporate physics or observational astronomy
- Sent a copy to Einstein – a “discussion” ensued and eventually these solutions are forgotten?

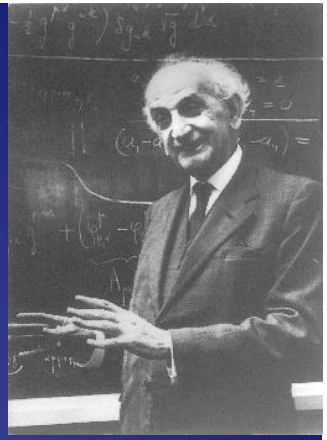
# Ludwik Silberstein (1924)



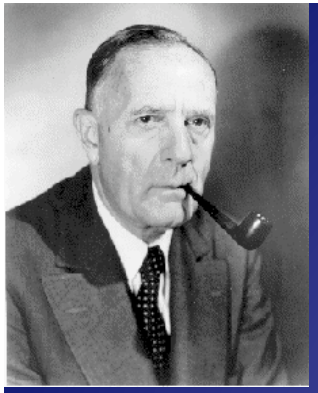
Argues for a **distance vs redshift** relation of the form $\Delta\lambda/\lambda=+/-r/R$ (red & blue shift!)

- Claims it agrees with observations of globular clusters (only uses 7 of 16 data pts)
- The “Silberstein Effect” is ridiculed

# Cornelius Lanczos (1922/3)



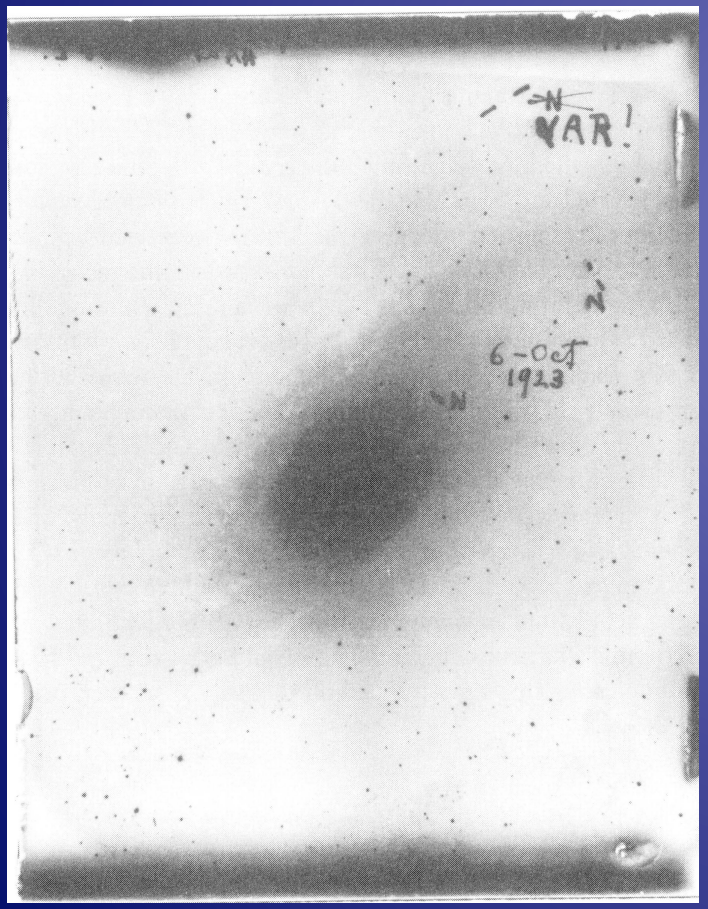
- 1922: Using a change of coordinates found a model where the radius varies hyperbolically with time $R \sim \cosh(ct/R_o)$
  - 1922 Phys. ZS. 23, 537 & 1923 Z. Phys. 17, 168
  - Inspired by a paper by Weyl 1923 Phys. Z. 24, 130
- Does NOT give up the static model in a physical sense
  - Transforms the de Sitter line element making it non-static such that one or more components of $g_{mn}$ depends on a time coordinate
  - $ds^2=c^2dt^2-F(t)(dx^2+dy^2+dz^2)$

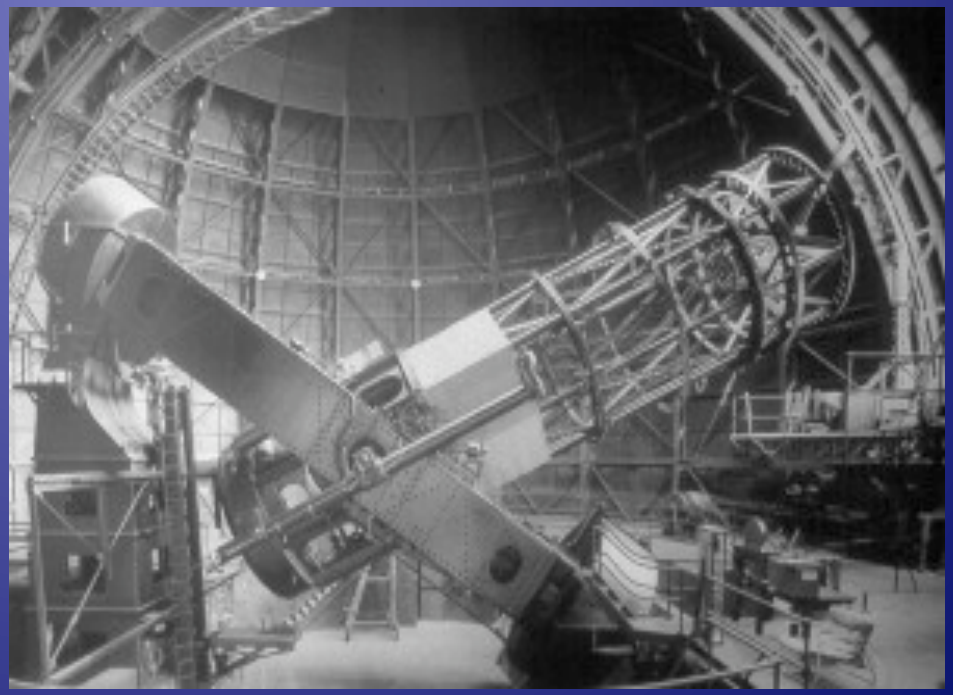


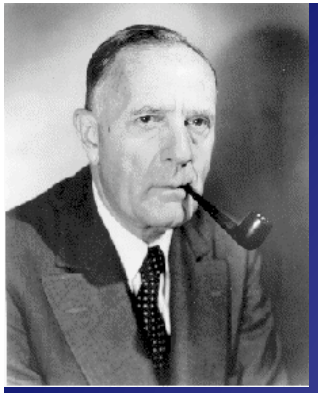
# Edwin Hubble (1923)

October 1923 finds Cepheid in Andromeda (M31)

- First found in a spiral nebula
- Done on the 100” Hooker





# Edwin Hubble (1925)

- Jan 1925 Publishes distance of 300 kpc
  - 300 kpc ~ 1 million light years
    - Small Magellanic Cloud is ~ 60 kpc
    - Milky Way is about 30 kpc in diameter
    - In Reality Andromeda is ~ 800 kpc away
- Establishes that spiral nebulae **ARE** external galaxies (vanMaanen?)
    - Supports island universe idea (Kant 1755)?
    - Partial resolution of Shapley-Curtis debate
- The Universe is more than the Milky Way!

Now that we know there is an external universe, how do those large radial velocities fit in?

# Knut Lundmark (1924-25)

- Is puzzled by Silberstein's derivations from Globular Clusters
- Says Globular Clusters are too close & sees no correlation between radial velocity & distance when using full sample
- Also tests Cepheids, Novae, O Stars, Eclipsing Variables, R Stars, N Stars

# Knut Lundmark (1924-25)

- Plots 38 nebular **distances vs radial velocity**
  - Refuses to fit a line to the data!!
  - “There may be a relation between the two quantities, although not a very definite one”
  - 1924 MNRAS 84, 747

# Knut Lundmark (1924)

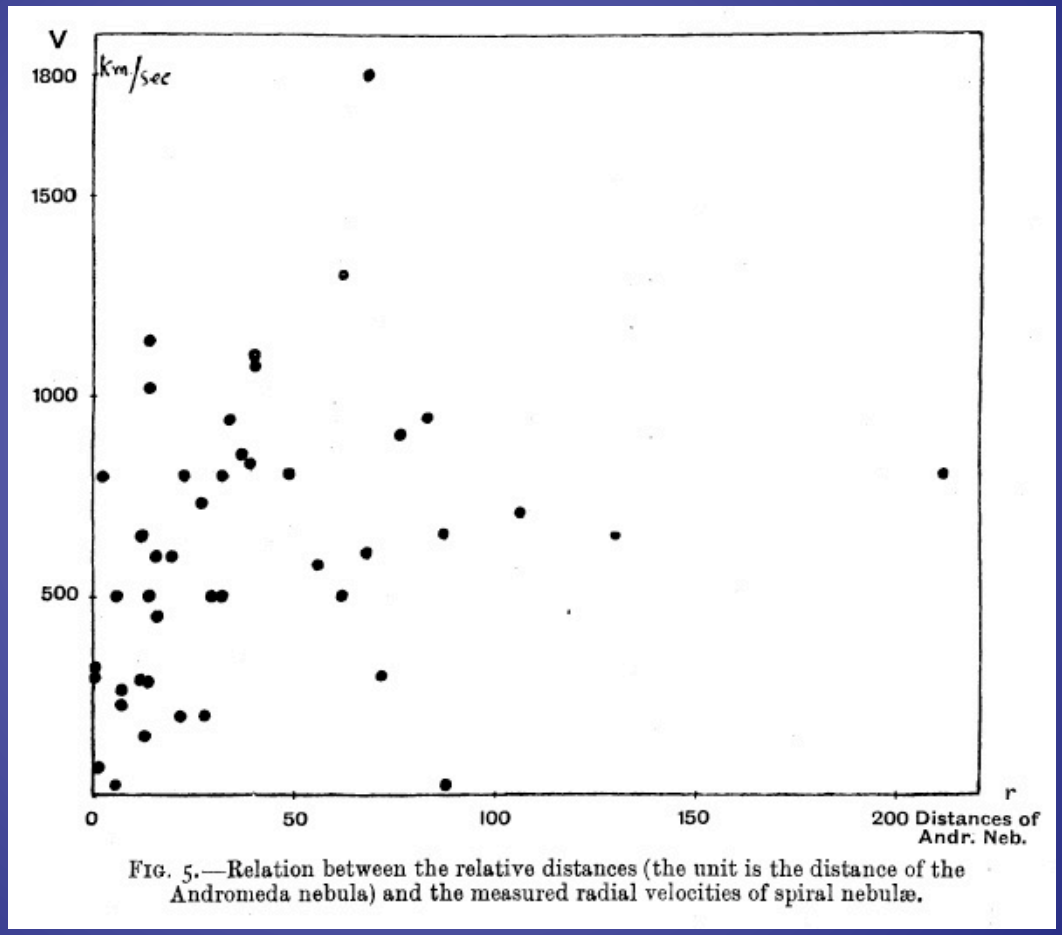
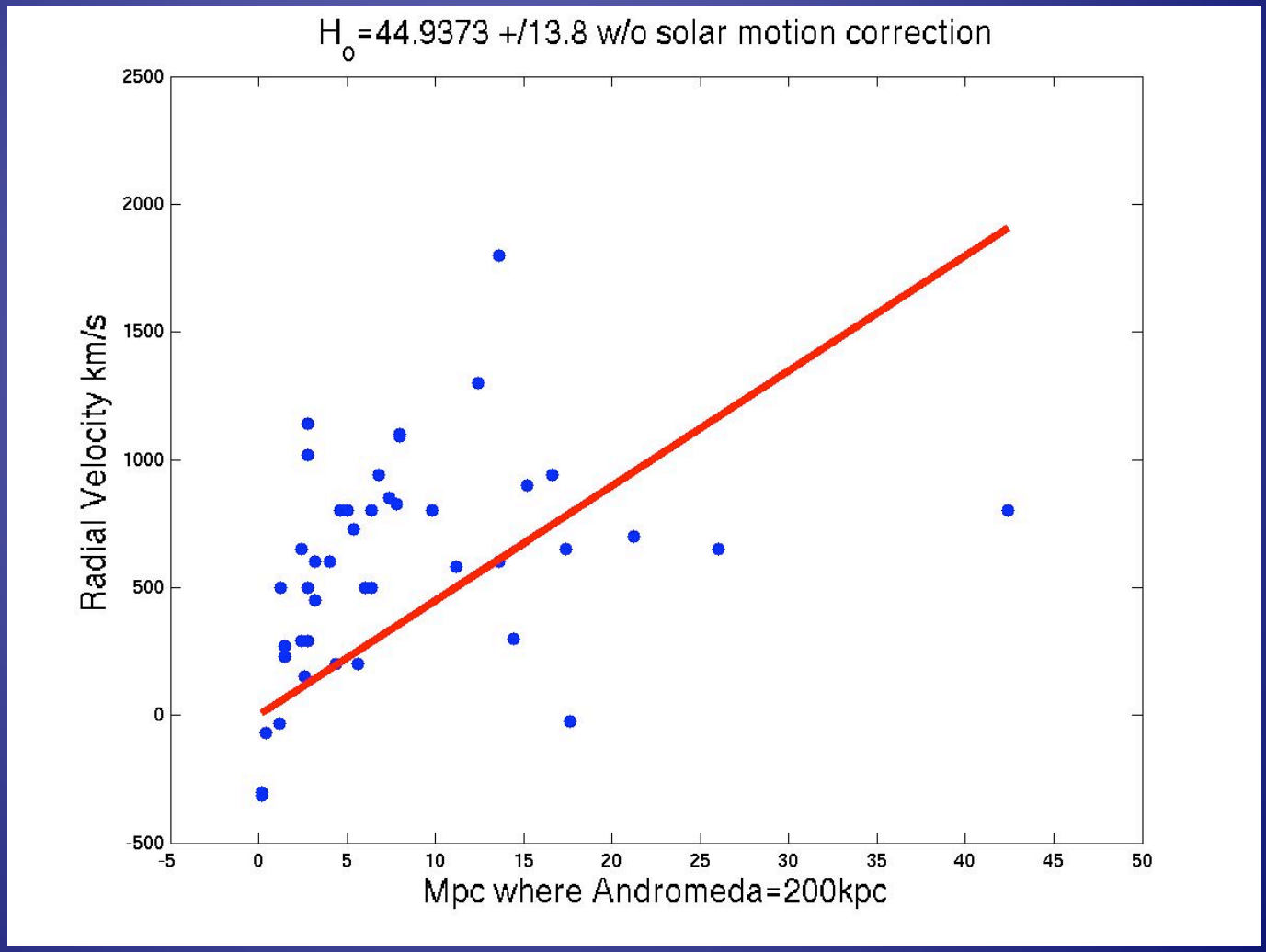
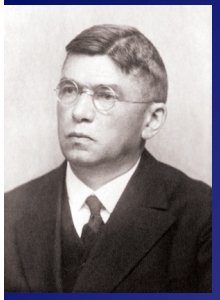



FIG. 5.—Relation between the relative distances (the unit is the distance of the Andromeda nebula) and the measured radial velocities of spiral nebulæ.

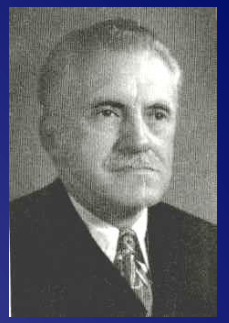
First published radial velocity vs distance **diagram**!

# Knut Lundmark (1924)





# Wirtz & Strömberg (1924/25)



- Wirtz (1924 AN 222, 21)
  - Uses data like that of Lundmark (1924) & claims a log-diameter (distance) vs velocity relation: v(km) = 2200–1200×log($D_m$)
- Strömberg (1925 ApJ 61, 353) [Mt Wilson]
  - Uses magnitudes as a proxy for distance
  - "no sufficient reason to believe there exists any dependence of radial motion upon distance from the sun"
  - Globular Cluster Relationship ➔

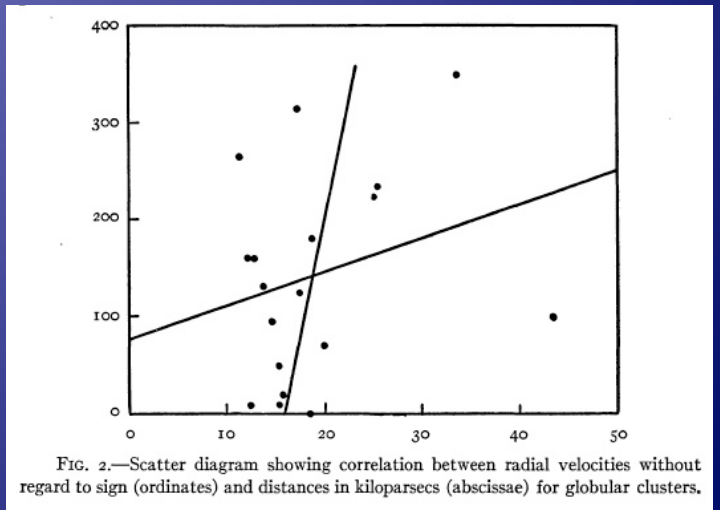



FIG. 2.—Scatter diagram showing correlation between radial velocities without regard to sign (ordinates) and distances in kiloparsecs (abscissae) for globular clusters.

# Georges Lemaitre (1925)

- Discusses a non-static de Sitter world
  - Linked it to current observations:

    "Our treatment evidences this non-static character of de Sitter's world which gives *a possible interpretation of the main receding motion of spiral nebulae*
  - No mention of Friedmann, Lanczos or Weyl

- Unlike Silberstein's previous work (1924) his treatment contained only redshifts
- No discussion of a Friedmann like expanding universe (yet)

# Georges Lemaitre (1927)

- Independently derives Friedman's equations with a time-dependent space curvature R(t)
  - Showed that the cosmological equations could be satisfied by an expanding universe
- The velocity of recession is *"the apparent Doppler effect due to the variation of the radius of the universe"*
- Very different understanding from Friedman?

# Georges Lemaitre (1927) cont'

- Derives a distance versus radial-velocity relationship (The Hubble Constant) for spiral nebulae via the data of:
  - Slipher ,G. Strömberg, Hubble (1926)
- **Using 42 galaxies he found values of 625 & 575 km/s/Mpc**
  - Mentions previous attempts by Lundmark (1924) and Stromberg (1925)

# Georges Lemaitre (1927) cont'

Unfortunately…

- Published in the Annales Scientifique Bruxelles
- Einstein called his physically expanding universe solution "abominable"
  - The 2nd time Einstein rejects this solution, why!?
- Paper is forgotten by everyone (Eddington) just like Friedman's!!
- Later was published in MNRAS in 1931 (thanks to Eddington) BUT without the Hubble constant numbers!!!!

vitesse de l'observateur qui produirait le même effet. Lorsque la source est suffisamment proche, nous pouvons écrire approximativement

$$\frac{v}{c} = \frac{R_2 - R_1}{R_1} = \frac{dR}{R} = \frac{R'}{R}\,dt = \frac{R'}{R}\,r$$

où $r$ est la distance de la source. Nous avons donc

(23) $$\frac{R'}{R} = \frac{v}{cr} \ .$$

Les vitesses radiales de 43 nébuleuses extragalactiques sont données par Strömberg[a].

La grandeur apparente $m$ de ces nébuleuses se trouve dans le travail de Hubble. Il est possible d'en déduire leur distance, car Hubble a montré que les nébuleuses extragalactiques sont de grandeurs absolues sensiblement égales (grandeur – 15,2 à 10 parsecs, les écarts individuels pouvant atteindre deux grandeurs en plus ou en moins), la distance $r$ exprimée en parsecs est alors donnée par la formule $\log r = 0{,}2\,m + 4{,}04$.

On trouve une distance de l'ordre de $10^6$ parsecs, variant de quelques dixièmes à 3,3 millions de parsecs. L'erreur probable résultant de la dispersion en grandeur absolue est d'ailleurs considérable. Pour une différence de grandeur absolue de deux grandeurs en plus ou en moins, la distance passe de 0,4 à 2,5 fois la distance calculée. De plus, l'erreur à craindre est proportionnelle à la distance. On peut admettre que, pour une distance d'un million de parsecs, l'erreur résultant de la dispersion en grandeur est du même ordre que celle résultant de la dispersion en vitesse. En effet, une différence d'éclat d'une grandeur correspond à une vitesse propre de 300 km, égale à la vitesse propre du Soleil par rapport aux nébuleuses. On peut espérer éviter une erreur systématique en donnant aux observations un poids proportionnel à

$$\frac{1}{\sqrt{1 + r^2}}$$

où $r$ est la distance en millions de parsecs.

Utilisant les 42 nébuleuses figurant dans les listes de Hubble et de Strömberg[b], et tenant compte de la vitesse propre du Soleil (300 km dans la direction $\alpha = 315°$, $\delta = 62°$), on trouve une distance moyenne de

a « Analysis of Radial Velocities of Globular Clusters and Non Galactic Nebulae », *Ap. J.*, vol. 61, 1925, p. 353. *Mt Wilson Contr.*, n° 292.

b Il n'est pas tenu compte de NGC 5 194 qui est associé à NGC 5 195. L'introduction des nuées de Magellan serait sans influence sur le résultat.





0,95 million de parsecs et une vitesse radiale de 600 km/sec, soit 625 km/sec à $10^6$ parsecs[a].

Nous adapterons donc

(24) $$\frac{R'}{R} = \frac{v}{rc} = \frac{625 \times 10^5}{10^6 \times 3{,}08 \times 10^{18} \times 3 \times 10^{10}} = 0{,}68 \times 10^{-27}\ \text{cm}^{-1} \ .$$

Cette relation nous permet de calculer $R_0$. Nous avons en effet, par (16),

(25) $$\frac{R'}{R} = \frac{1}{R_0\sqrt{3}}\sqrt{1 - 3y^2 + 2y^3}$$

où nous avons posé

(26) $$y = \frac{R_0}{R} \ .$$

D'autre part, d'après (18) et (26),

(27) $$R_0^2 = R_E^2\, y^3$$

et donc

(28) $$3\left(\frac{R'}{R}\right)^2 R_E^2 = \frac{1 - 3y^2 + 2y^3}{y^3} \ .$$

Introduisant les valeurs numériques de $R'/R$ (24) et de $R_E$ (19), il vient

$$y = 0{,}0465.$$

On a alors :

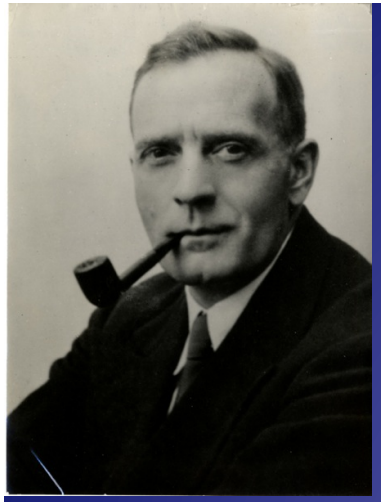
$$R = R_E\sqrt{y} = 0{,}215\ R_E = 1{,}83 \times 10^{28}\ \text{cm} = 6 \times 10^9\ \text{parsecs}$$

$$R_0 = Ry = R_E\, y^{3/2} = 8{,}5 \times 10^{26}\ \text{cm} = 2{,}7 \times 10^8\ \text{parsecs} = 9 \times 10^8\ \text{années de lumière.}$$

a En ne donnant pas de poids aux observations, on trouverait 670 km/sec à $1{,}16 \times 10^6$ parsecs, 575 km/sec à $10^6$ parsecs. Certains auteurs ont cherché à mettre en évidence la relation entre $v$ et $r$ et n'ont obtenu qu'une très faible corrélation entre ces deux grandeurs. L'erreur dans la détermination des distances individuelles est du même ordre de grandeur que l'intervalle que couvrent les observations et la vitesse propre des nébuleuses (en toute direction) est grande (300 km/sec d'après Strömberg), il semble donc que ces résultats négatifs ne sont ni pour ni contre l'interprétation relativistique de l'effet Doppler. Tout ce que l'imprécision des observations permet de faire est de supposer $v$ proportionnel à $r$ et d'essayer d'éviter une erreur systématique dans la détermination du rapport $v/r$. Cf. Lundmark, « The determination of Curvature of Space Time in De Sitter's World », *M.N.*, vol. 84, 1924, p. 747, et Strömberg, art. cité.

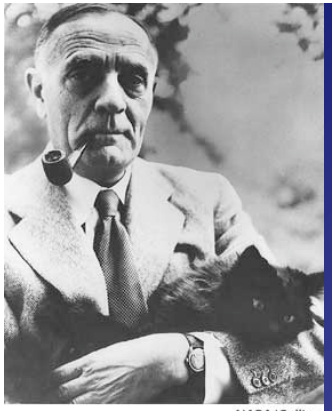
# Edwin Hubble (1929)

- Uses “distances” to 24 nebulae & redshifts to derive a linear velocity-distance relation
  - Mentions Lundmark’s work
  - No mention of Lemaitre or Robertson
- 1931: Accuracy increased with 40 more
  - Debate on linear relationship ended here?
  - **Einstein abandons cosmological constant**
- But does Hubble actually believe in an expanding universe?

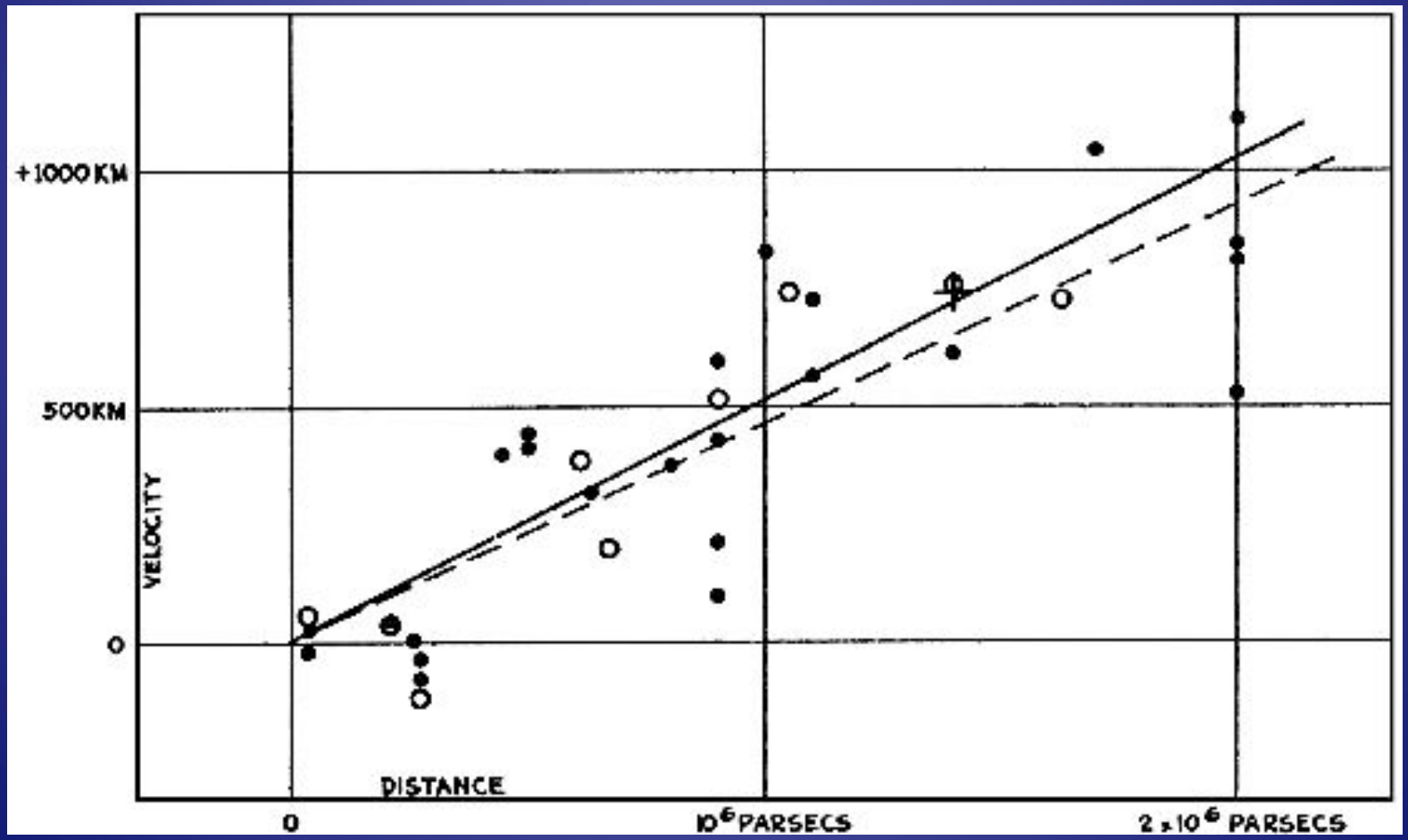


# Edwin Hubble (1929)

- "A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE"
  - Proc. Natl. Acad. Sci. USA 15, 168–173
  - $v=H_o \times D$
- 24 Objects: $H_o$=465 +/- 50 km/s/Mpc
- 9 "Groups": $H_o$=513 +/- 60 km/s/Mpc
- **$t=1/H_o \sim 2 \times 10^9$ yr old (very young?!)**


NARA/Colliers

# Edwin Hubble (1929)



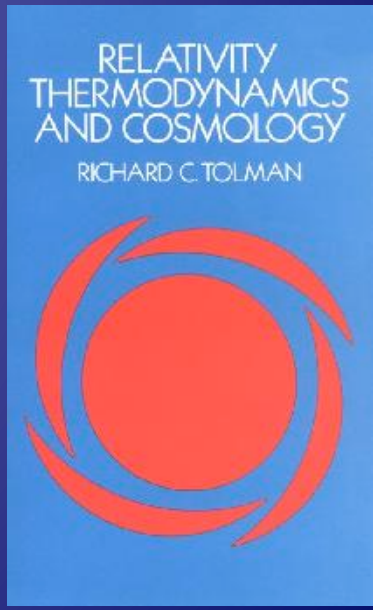
# Lemaitre & Oort (1931)

- Lemaitre: speculates Universe began as a primeval atom (May 9, 1931 Nature)
- Lemaitre's 1927 paper is finally published (Lemaitre 1931 MNRAS 91, 483)
  - But does not contain his values of $H_o$
- Oort: $H_o$=290 km/s/Mpc ~ 3.3 Gyr
  - Earth and Age of Universe nearly consistent

http://www.astro.ucla.edu/~wright/CosmoCalc.html

# Richard Tolman (1930s)

- Shows radiation in an expanding homogeneous universe would cool & maintain its Black Body spectrum
- 1934: Publishes “Relativity, Thermodynamics, & Cosmology”
  - The bounce from an **oscillating universe** could produce entropy, largely in the form of a sea of thermal radiation



# Karl Guthe Jansky: May 5, 1933

## NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

### Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

### DIRECTION IS UNCHANGING

### Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

### ITS INTENSITY IS LOW

**Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signaling.**

Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy was announced yesterday by the Bell Telephone Laboratories. The discovery was made during research studies on static by Karl G. Jansky of the radio research department at Holmdel, N. J., and was described by him in a paper delivered before the International Scientific Radio Union in Washington.

The galactic radio waves, Mr. Jansky said, differ from the cosmic rays and also from the phenomenon of cosmic radiation, described last week before the American Philosophical Society at Philadelphia by Dr. Vesto M. Slipher, director of the Lowell Observatory at Flagstaff, Ariz.

Unlike the cosmic ray, which comes from all directions in space, does not vary with either the time of day or the time of the year, and may be either a photon or an electron, the galactic waves, Mr. Jansky pointed out, seem to come from a definite source in space, vary in intensity with the time of day and time of the year, and are distinctly electro-magnetic waves that can be picked up by a radio set.

**New Waves Have High Frequency.**

The cosmic radiation discovered by Dr. Slipher is a mysterious form of light apparently radiated independently of starlight, originating, Dr. Slipher concluded, at some distance above the earth's surface, and possibly produced by the earth's atmosphere.

The galactic radio waves, the announcement says, are short waves, 14.6 meters, at a frequency of about 20,000,000 cycles a second. The intensity of these waves is very low, so that a delicate apparatus is required for their detection.

Unlike most forms of radio disturbances, the report says, these newly found waves do not appear to be due to any terrestrial phenomena, but rather to come from some point far off in space—probably far beyond our solar system.

If these waves came from a terrestrial origin, it was reasoned, then they should have the same intensity all the year around. But their intensity varies regularly with the time of day and with the seasons, and they get much weaker when the earth, moving in its orbit, interposes itself between the radio receiver and the source.

A preliminary report, published in the Proceedings of the Institute of Radio Engineers last December, described studies which showed the presence of three separate groups of static: Static from local thunderstorms, static from distant thunderstorms, and a "steady hiss type static of unknown origin." Further studies this year determine the unknown origin of this third type to be from the direction of the centre of the Milky Way, the earth's own home galaxy.

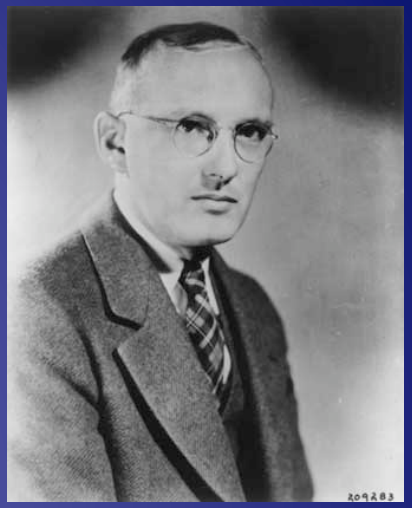
**Direction of Arrival Fixed.**

The direction from which these waves arrive, the announcement asserts, has been determined by investigations carried on over a considerable period. Measurements of the horizontal component of the waves were taken on several days of each month for an entire year, and by an analysis of these readings at the end of the year their direction of arrival was disclosed.

"The position indicated," it was explained, "is very near to the point where the plane in which the earth revolves around the sun crosses the centre of the Milky Way, and also to that point toward which the solar system is moving with respect to the other stars.

"Further verification of this direction is required, but the discovery, like that of the cosmic rays and of cosmic radiation, raises many cosmological questions of extreme interest."

There is no indication of any kind, Mr. Jansky replied to a question, that these galactic radio waves constitute some kind of interstellar signalling, or that they are the result of some form of intelligence striving for intra-galactic communication.



1933: The discovery of extraterrestrial radio waves, but NOT intra-galactic communication ☹

# Arthur Stanley Eddington

- Promoted the idea of the expanding universe starting ~1930
- Realized the Intimate relationship between Lemaitre's 1927 paper and Hubble & Humason observations
  - e.g. 1930 MNRAS 30, 668

# Part II
# From Expanding Universe to The Cosmic Microwave Background

- We now have theoretical & *some* observational evidence of an expanding Universe

- However, where is Tolman's black body radiation?

# Unknown signals and temperatures

- Starting in 1940 and 1941 several observations are made of Tolman's Thermal Background Radiation, but are not understood as such

  **(The Cosmic Microwave Background – CMB)**

- We will jump between theory & observation for some years until we find something interesting…

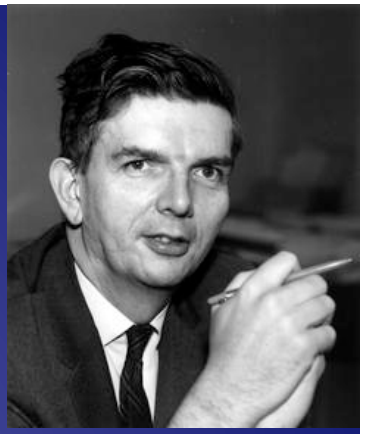
# Adams, Dunham, Merrill, McKellar

- 1940: Adams, Dunham & Merrill (Mt. Wilson)
  - Observe several unidentified absorption lines including one at 3874.61A in the interstellar medium
- 1940: McKellar (Dominion) identifies CN line
  - It is the first molecule discovered in interstellar space! (along with CH & NaH)
  - ‘the maximum effective temperature of interstellar space would be 2.7°, 2.1° or 0.8°K”

# Hertzberg: 1950

- Spectra of Diatomic Molecules
  - "From the intensity ratio of the lines with *K=0 & K=1* ***a rotational temperature of 2.3° K follows, which has of*** **course only a very restricted meaning**"
  - On page 44 of his new book Peebles claims to know the meaning… **collisional excitation**.

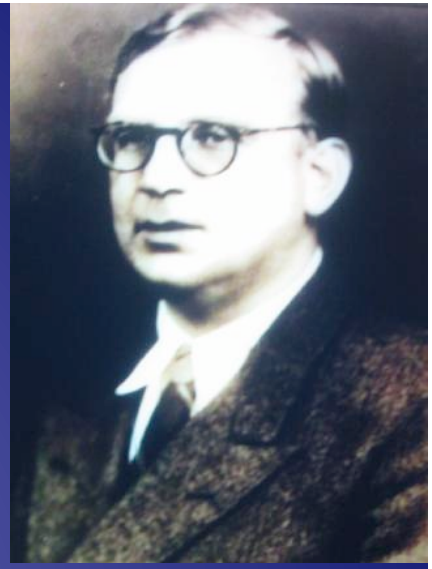
# Robert Dicke (1946)



Phys Rev v70, p340 “Atmospheric Absorption **Measurements** with a Microwave Radiometer“

- Found “very little (< 20°K) radiation from **cosmic matter** at the radiometer wavelengths”
- “However, the absolute accuracy of this result was not high (±20°K) … a small amount of ***cosmic noise*** if distributed uniformly in direction does not introduce much error…”
- T<20±20°K is clearly consistent with T=0°K

# George Gamow (1946)



Developing a big bang model of The Universe…

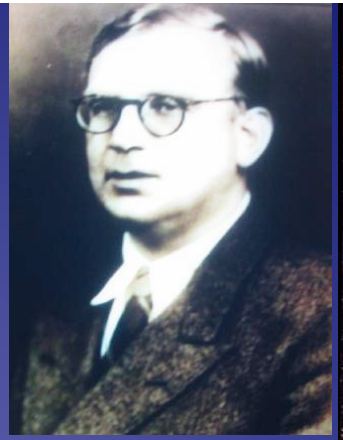
- Tries to explain the abundance of metals in The Universe via **"Big Bang Nucleosynthesis"**
- Estimates the early rate of expansion of a matter dominated Friedmann-Lemaitre model
- Supports Tolman's "general theory of the expanding universe"

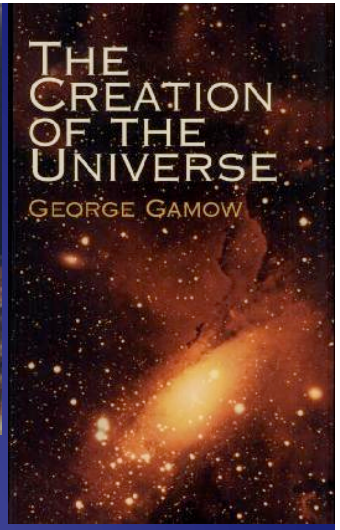
# Alpher (Bethe) Gamow Herman


- 1948: $\alpha\beta\gamma$ paper: Alpher, Bethe, Gamow - Chemical Abundances in Big Bang Nucleosynthesis
- 1948 Alpher & Herman: Predict a black body spectrum “about 5°K” should exist (Nature 162,774)
- A&H visit Hagan(?) NRL in1948/49 and are told 5°K radiation is too hard to measure (Weber)

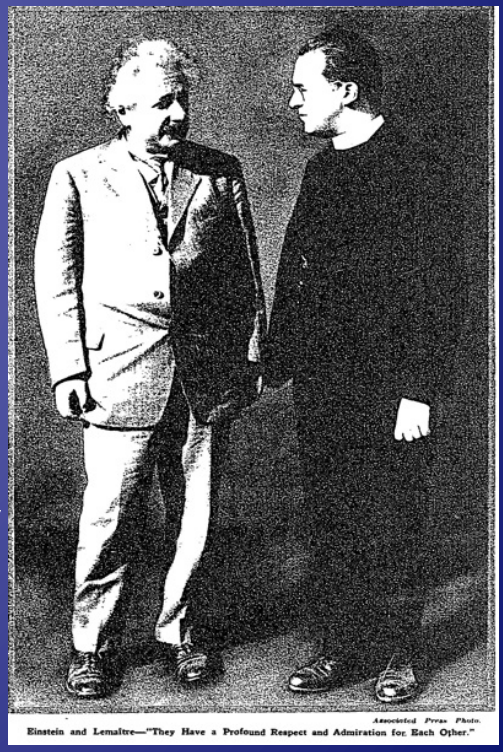
# George Gamow (1952)

## The end of Big Bang Theory?






- 1952: T=50K in "The Creation of The Universe", page 40
- Alpher & Herman go on to other fields
- Failure to account for creation of chemical elements in the theory
- Gamow is ignored, Einstein is hostile?
  - 1927: "Your calculations are correct, but your grasp of physics is abominable"
  - 1933: "This is the most beautiful and satisfactory explanation of creation to which I have ever listened". (January 1933)
- 12 yrs of theoretical darkness reign…



Einstein and Lemaître—"They Have a Profound Respect and Admiration for Each Other."

NYTimes Mag
Feb 19, 1933

# 1946-56: Hoyle, Bondi & Gold, $B^2FH$

Hot Big Bang cannot produce heavy elements?
Alternatives to Lemaitre's Big Bang Theory?

- 1946: Hoyle: collection of very hot nuclei would assemble into iron
- 1948: (Hoyle) & (Bondi & Gold) publish their Steady-State Theories of The Universe
- 1954: Hoyle finds stellar fusion can synthesize elements between carbon and iron
- 1956: $B^2FH$ Theory of Stellar Nucleosynthesis
- 1967: Wagoner, Fowler, Hoyle light-element Nucleosynthesis

# 1950: Fred Hoyle & The Big Bang

During a Radio Interview Hoyle ridicules (vividly describes?) the “primeval atom” theory by calling it

‘**The Big Bang**’

# 1948/1953: The First Five Minutes?


Cartoon published in 1948 in *The Washington Post* was inspired by a statement in Alpher's dissertation to the effect that the period of nucleosynthesis in the early universe lasted about 5 minutes.

Alpher, Follin, Herman 1953 PhysRev ➔

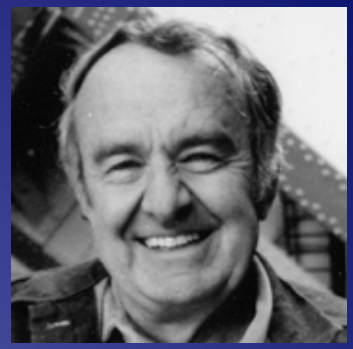
TABLE IV. Timetable of events in the early epochs of the expanding universe.

| Temperature (Mev) | Remarks: Neutrino ≡ antineutrino | Remarks: Neutrino ≠ antineutrino |
|---|---|---|
| >100 | Region of doubtful validity of the field equations where $\rho_\gamma$ exceeds nuclear density. | |
| ~100 | Thermodynamic equilibrium prevails. | |
| | $\rho_\gamma \cong 1.2\times10^{13}$ g/cm³<br>$\rho_\mu = (7/4)\rho_\gamma$, $\rho_\pi = (3/2)\rho_\gamma$<br>$\rho_\nu = (7/8)\rho_\gamma$, $\rho_e = (7/4)\rho_\gamma$<br>$t \cong 6.3\times10^{-5}$ sec | Same as for $\nu \equiv \nu^*$ except<br>$\rho_\nu = (7/4)\rho_\gamma$<br>$t \cong 5.9\times10^{-5}$ sec |
| ~100 — ~10 | Mesons annihilate converting energy into photons, electrons, and neutrinos. | |
| ~10 | Neutrinos are freezing-in during this period. | |
| | $\rho_\gamma \cong 1.2\times10^{9}$ g/cm³<br>$\rho_\mu \sim 10^{-6}\rho_\gamma$, $\rho_\pi \sim 10^{-6}\rho_\gamma$<br>$\rho_\nu = (7/8)\rho_\gamma$, $\rho_e = (7/4)\rho_\gamma$<br>$t \cong 8.7\times10^{-3}$ sec | Same as for $\nu \equiv \nu^*$ except<br>$\rho_\nu = (7/4)\rho_\gamma$<br>$t \cong 7.8\times10^{-3}$ sec |
| ~10 — ~2 | Continued adiabatic expansion of universe with $T_\gamma \cong T$ despite negligible interaction of neutrinos with medium. | |
| ~2 | Start of electron-positron annihilation. | |
| | $\rho_\gamma \cong 1.9\times10^{6}$ g/cm³<br>$\rho_\mu = \rho_\pi \sim 0$<br>$\rho_\nu \cong (7/8)\rho_\gamma$, $\rho_e = (7/4)\rho_\gamma$<br>$t \cong 0.22$ sec | Same as $\nu \equiv \nu^*$ except<br>$\rho_\nu \cong (7/4)\rho_\gamma$<br>$t \cong 0.20$ sec |
| ~2 — ~0.05 | Electron-positron annihilation, converting energy into photons. Neutrinos cool adiabatically relative to remaining particles, the latter maintaining thermodynamic equilibrium. [See Tables I and II for more details during this epoch.] The neutron-proton abundance ratio reaches the free decay value, 4.5:1 — 6.0:1, at $T \sim 0.2$ Mev. Nucleogenesis begins at $T \sim 0.2$ Mev. | |
| ~0.05 | Nucleogenesis is well under way. | |
| | $\rho_\gamma \cong 0.72$ g/cm³<br>$\rho_\nu \cong 0.24\rho_\gamma$, $\rho_e \sim 0$<br>$t \cong 600$ sec | $\rho_\gamma \cong 0.72$ g/cm³<br>$\rho_\nu \cong 0.47\rho_\gamma$, $\rho_e \sim 0$<br>$t \cong 550$ sec |
| ~0.03 | Nucleogenesis essentially complete except for charge adjustment by $\beta$ decay. | |
| | $t \sim 30$ min | |
| ~0.03 Mev — ~1 kev | Thermonuclear reactions among some of the light elements, *viz.*, Li, Be, B, D with H, continue during this period. | |
| ~0.015 ev | At $t \sim 10^8$ yr, $T \sim 170$°K and $\rho \sim 10^{-26}$ g/cm³, galaxies probably form. | |

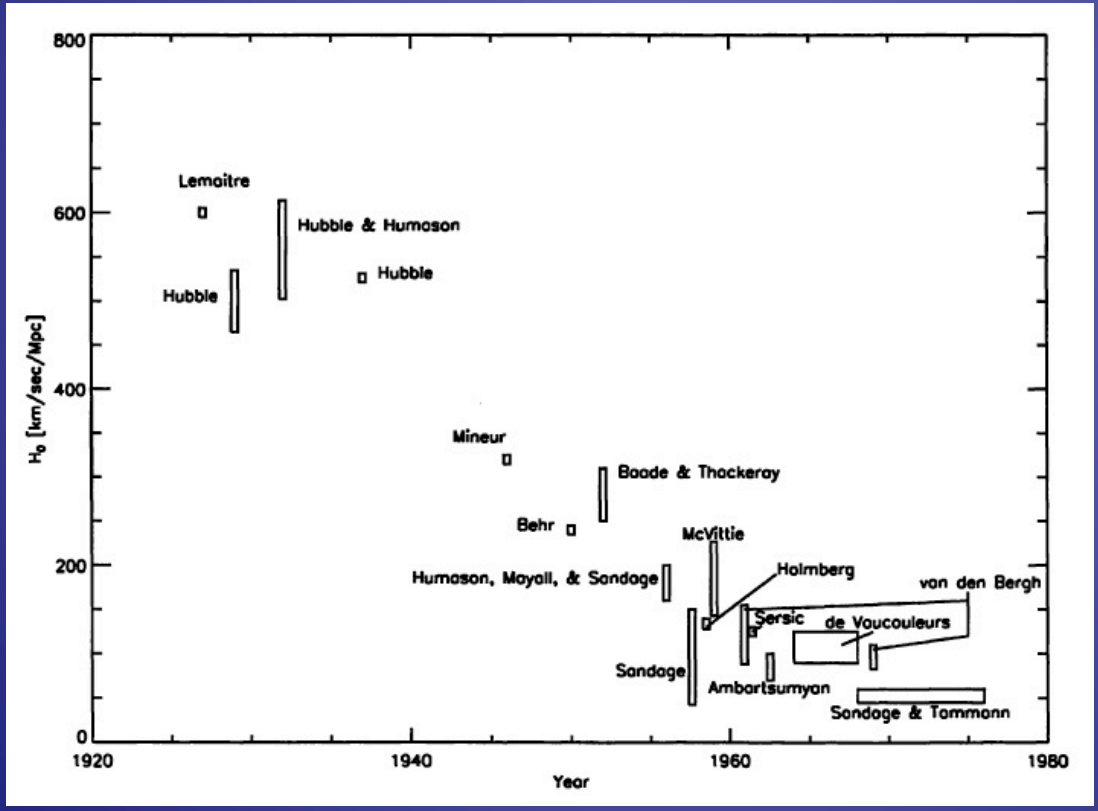
# 1955 & 57 Le Roux & Shmaonov

- Emile Le Roux's survey found an isotropic emission T = 3 ± 2 K
  - Suggested it was of extragalactic origin?
- Tigran Shmaonov measured a direction independent radiation at $\lambda$=3.2cm
  - "The absolute effective temp. of radiation background … appears to be 4 ± 3 K"

# 1958 Allan Sandage



$H_o$ gives an age of ~$13 \times 10^9$ years




V. Trimble '96

# Echo I Satellite (1960)

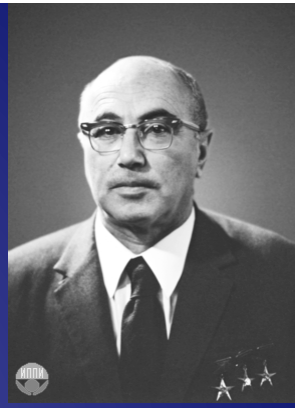
- Bell Laboratories (Holmdel NJ) constructs a very sensitive radio telescope at ~13cm
- To study reception of radio signals **passively** reflected from Echo I satellite

# Echo I Satellite

# Early 1960s Work: Dicke & Peebles

- Bob Dicke & Jim Peebles re-derive Gamow & Alpher's CMB prediction
  - They recall Dicke's 1946 paper with T<20K
  - Dicke & Peebles 1965/03 predict $T_{cmb}$=10K
- Dicke, Peebles, Wilkinson, Roll & others start construction of a small radio telescope to look for the Big Bang afterglow

# Early 1960s Theoretical Work



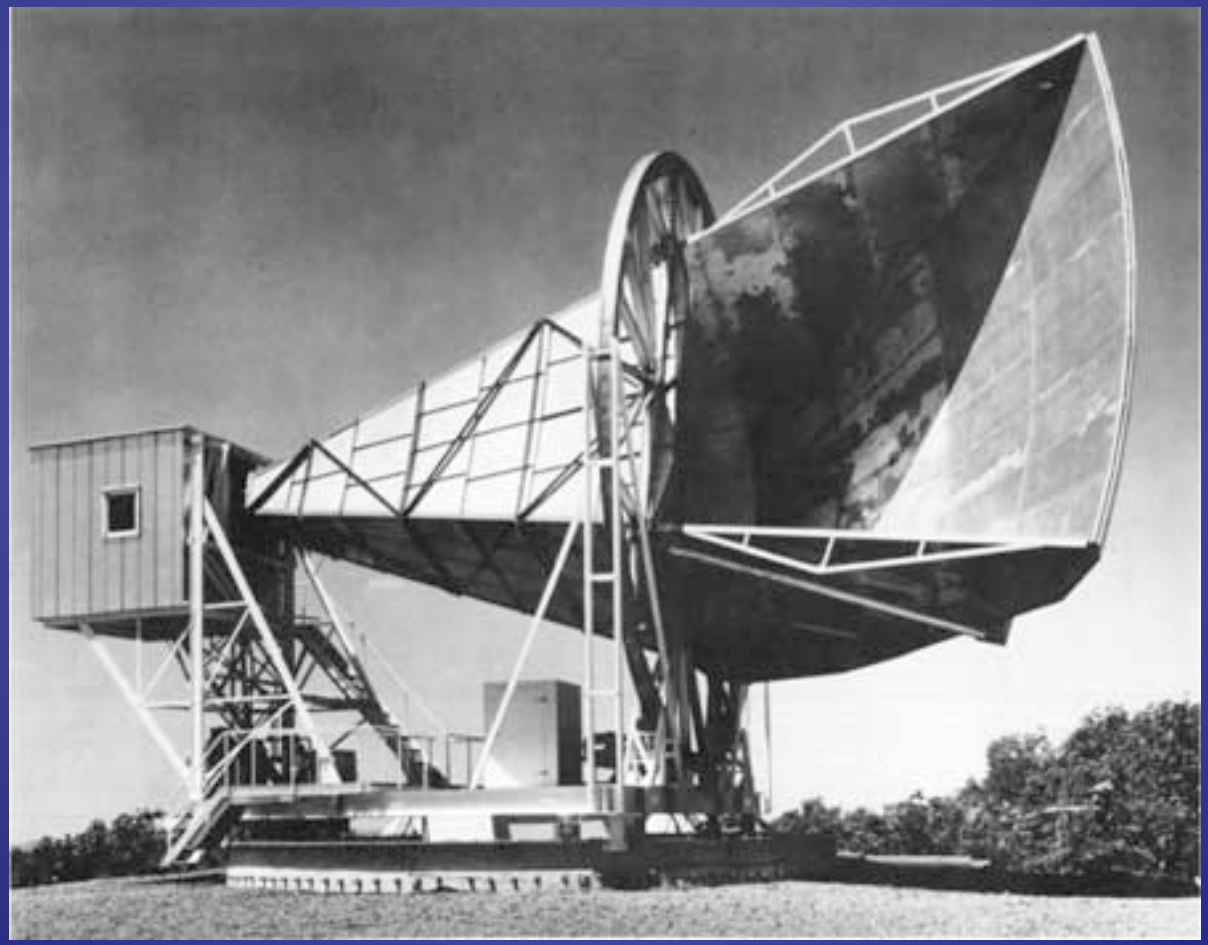
Yakov Zel'dovich

- Recalls Gamow's work
- Calculates T=20K
- Tells Andrei Doroshkevich & Igor Novikov to see if it is detectable (theoretically)
- Was to support his Cold Big Bang Model
  - He didn't think you could synthesize elements in the Hot Big Bang model of Gamow et al.
  - First revival of Big Bang theory since Gamow, Alpher & Herman's work

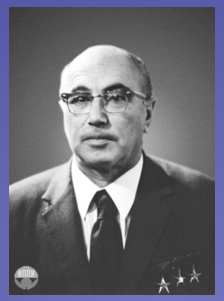
# Bell Labs Radio Telescope

- 1963: The Telescope starts to be used for Radio Astronomy at ~7.3cm
  - Used a left over receiver from the Telstar project
- Was the most sensitive instrument in the world for the detection of radio waves from large areas of the sky

# Bell Labs Radio Telescope



# 1964: Doroshkevich & Novikov



- They show that the *Relict Radiation* should be **detectable** (contrary to Gamow's comments)
- It should be found in the microwave regime **where other galactic sources have weak emissions**

# 1964: Doroshkevich & Novikov



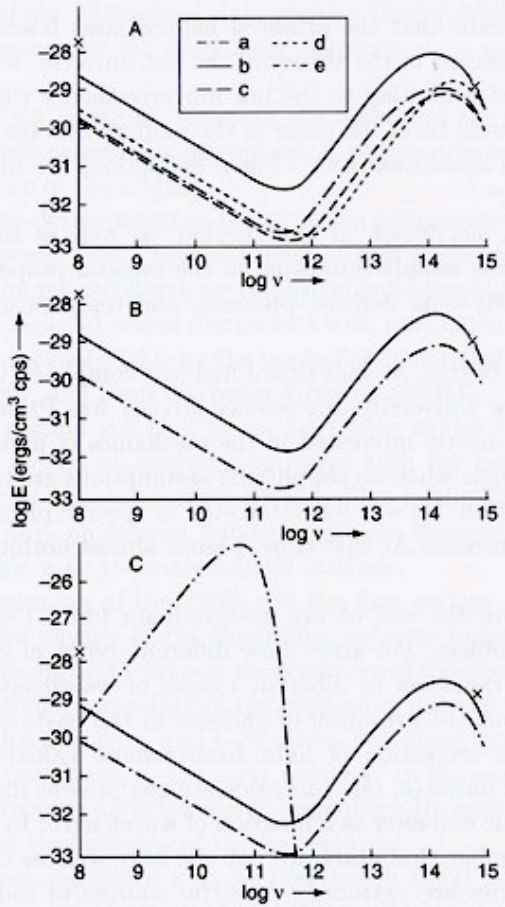



Fig. 4.5. From Doroshkevich and Novikov (1964). Spectrum of the metagalaxy. Curves (a)–(d): the integrated radiation from galaxies under several assumptions about the cosmology and the evolution of the galaxies. Curve (e): equilibrium Planck radiation with $T = 1\,\mathrm{K}$. Crosses denote experimental points. 

# 1964: Doroshkevich & Novikov

- “Measurements reported in Ohm 1961 give T=2.3±0.2°K, which coincides with theoretically computed atmospheric noise (2.4°K). Additional measurements in this region (preferably on an artificial earth satellite) will assist in final solution of the problem of the correctness of the Gamow theory”
- The Ohm 1961 observations were at Bell Labs!
- Really was T=3.3±3.72°K (see Ohm Table II)
- The D&N paper is unnoticed by everyone
  - Princeton (Dicke) to Holmdel (Ohm) is ~35 miles
  - Moscow (D&N) to Holmdel (Ohm) is ~4600 miles
- Jakes (1963) repeats for Telstar project,T=2.5K

# 1961 Ohm Table II



TABLE II — SOURCES OF SYSTEM TEMPERATURE

| Source | Temperature |
|---|---|
| Sky (at zenith) | 2.30 ± 0.20°K |
| Horn antenna | 2.00 ± 1.00°K |
| Waveguide (counter-clockwise channel) | 7.00 ± 0.65°K |
| Maser assembly | 7.00 ± 1.00°K |
| Converter | 0.60 ± 0.15°K |
| Predicted total system temperature | 18.90 ± 3.00°K |

the temperature was found to vary a few degrees from day to day, but the lowest temperature was consistently 22.2 ± 2.2°K. By realistically assuming that all sources were then contributing their fair share (as is also tacitly assumed in Table II) it is possible to improve the over-all accuracy. The actual system temperature must be in the overlap region of the measured results and the total results of Table II, namely between 20 and 21.9°K. The most likely minimum system temperature was therefore

$$T_{\text{system}} = 21 \pm 1°\text{K}.^*$$

The inference from this result is that the "+" temperature possibilities of Table II must predominate.

# Bell Labs Telescope - Astronomy

- Original intent was to measure radiation from interstellar emission in our galaxy
- Astronomers Penzias & Wilson found a source of noise that was direction independent
- The source had to be instrumental or cosmic

# Penzias & Wilson 1965

- Penzias mentions the noise “problem” to his friend Bernie Burke
- Burke recalls hearing about a talk by Jim Peebles via Ken Turner.
- Peebles mentioned a 10K radiation from The Big Bang they (Princeton) want to detect

# Penzias & Wilson

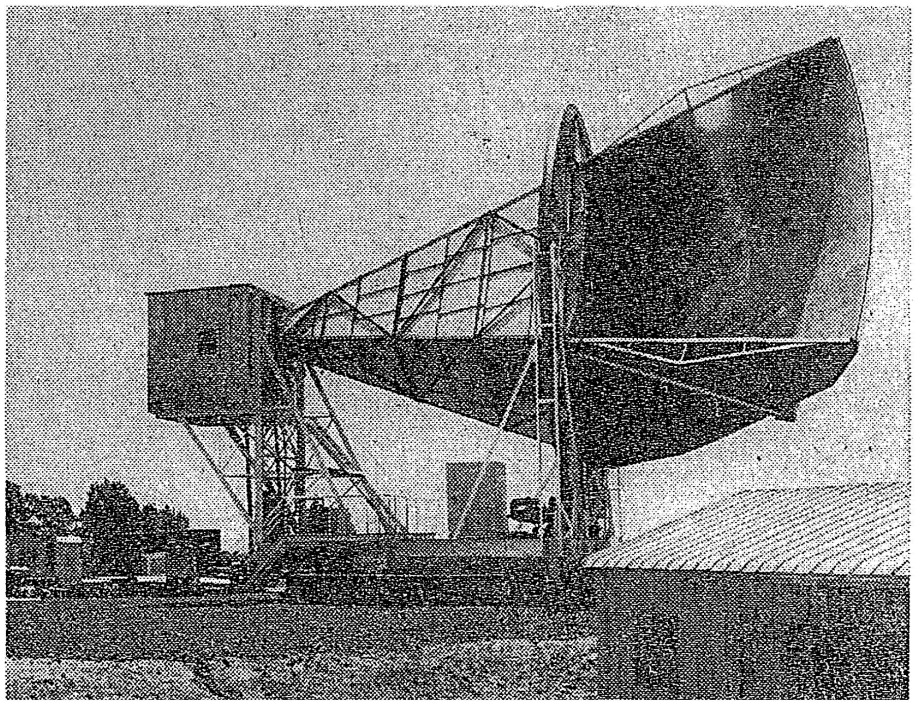
# Penzias, Wilson, Dicke

- Penzias contacts Dicke about his noise
- Dicke realizes that Penzias & Wilson have detected the Cosmic Microwave Background
- Found temperature to be closer to 3°K
  - Not Zeldovich's 20°K from 1963
  - Not Dicke's 10°K from 1964 (theory) nor his 20°K (measured) from 1946
  - **Closer to Alpher & Herman's 1948 5°K**

# 1965: Penzias, Wilson, Dicke

- Publish two papers in The Astrophysical Journal on the detection of the CMB
  - One is a theory paper by Dicke et al.
  - The other is an experimental paper by Penzias & Wilson
  - **Submitted both** on May 13, 1965
  - BUT On May 21st there are leaks

# Signals Imply a 'Big Bang' Universe



Horn antenna, used in space exploration, at the Bell Laboratories in Holmdel, N. J.

By WALTER SULLIVAN

Scientists at the Bell Telephone Laboratories have observed what a group at Princeton University believes may be remnants of an explosion that gave birth to the universe.

These remnants are thought to have originated in the burst of light from that cataclysmic event.

Such a primordial explosion is embodied in the "big bang" theory of the universe. It seeks to explain the observation that virtually all distant galaxies are flying away from the earth. Their motion implies that they all originated at a single point 10 or 15 billion years ago.

The Bell observations, made by Drs. Arno A. Penzias and Robert W. Wilson from a hilltop in Holmdel, N. J., were of radio waves that appear to be flying in all directions through the universe. Since radio waves and light waves are identical, except for their wavelength, these are thought to be remnants of light waves from the primordial flash.

The waves were stretched into radio waves by the vast expansion of the universe that has occurred since the explosion and release of the waves from the expanding gas cloud born of the fireball.

In what may prove to be one of the most remarkable coincidences in scientific history, the existence of such waves was predicted at

Continued on Page 18, Column 1

The New York Times
Published: May 21, 1965


# Signals Imply a 'Big Bang' Universe

Continued From Page 1, Col. 4

Princeton University at the same time that the scientists at the Bell Laboratories were puzzling over an observation of almost identical waves that they could not explain.

The Princeton group, led by Dr. Robert H. Dicke, Professor of Physics, was unaware of the Bell observation. Those at Bell had not heard of the Princeton prediction.

Like the recent discovery of objects, known as quasars, that lie near the fringes of the observable universe, the new observations may enable scientists to chose the correct picture of the universe: Is it infinite or limited in extent? Is it eternal and unchanging. Was it born in a single "big bang," or is it oscillating?

It is clear that Dr. Dicke and others would like to see an oscillating universe come out triumphant. The idea of a universe born "from nothing" in a single explosion raises philosophical as well as scientific problems.

An oscillating universe gets around the problem of origin. The galaxies fly apart in the manner currently observed. Then, at a certain point, they begin to fall back together again.

Finally, the night sky becomes brilliant with the light of converging galaxies. In a frightful cataclysm they fall together into a mass of fragmented atoms, then burst forth as a new fireball. This scatters hydrogen in all directions, from which new elements and new galaxies are formed.

### Quasar Observations

The observations of quasars from Mount Palomar in California have persuaded Dr. Allan R. Sandage of the observatory there that the universe may be oscillating at a rate of one "bang" every 82 billion years. However, further observations are needed for a clear-cut answer, he said in a recent telephone interview.

The study of the Bell Laboratories' observation at Princeton likewise leaves open the question of whether there has been but one explosion or the universe oscillates. However, both Dr. Sandage and Dr. Dicke clearly doubt the steady state theory in which there is no explosion at all.

Since, in this concept, the age of the universe is infinite, constant expansion would long since have carried all galaxies beyond our range of vision. Hence the theory demands the constant creation of new matter between galaxies to fill the gap.

The Holmdel observations were made with a horn-like antenna designed for experiments in space communications. The antenna played a key role in the development of the Telstar satellite system.

It stands on a hill not far from the field where another Bell Laboratories researcher, Karl G. Jansky, made the discovery in the 1930's that gave birth to a new science: radio astronomy.

Research with the horn antenna in recent years has been directed toward cleaning the receiver system of noise inherent in such systems—the hum in a typical receiver, for example.

A black body at a certain temperature emits a certain pattern of radio waves and hence such "system noise" is expressed in terms of temperature.

New devices, in particular the traveling wave maser, have greatly reduced the system noise in radio receivers and have played a major role in making satellite communications a reality.

In the research at Holmdel it was evident that some of the observed noise came from the system; some came from the warm envelope of air around the earth and a small amount came from the Milky Way galaxy and other galaxies.

### Unexplained Noise Remained

Yet there was always an unexplained residue. So long as the operational requirements of Telstar were paramount, little attention was paid to this residue, but more recently Drs. Penzias and Wilson decided to try for a "cleaner" system.

Working on the Telstar frequency of 4,000 megacycles (a wavelength of 7.3 centimeters) they still were unable to eliminate the left-over noise. They took the huge antenna apart, machined its moving parts and subjected its electric circuits to scrutiny comparable to that used in preparing a manned spacecraft. Perhaps, they thought, radio emissions were leaking into the antenna from something behind it.

Hence they carted a radio transmitter around nearby fields, testing to see if its emissions entered the system. They did not. Finally they reassembled the whole contraption and found the emissions were still there.

They anticipated 2.3 degrees of noise from the air, and one degree from the antenna, apart from 20 degrees from the receiver, which they had effectively canceled out. The noise to be expected from the Milky Way and other galaxies on that frequency was negligible.

The researchers were baffled and reported as much to their colleagues. It was then that someone told them of the proposal by the Princeton group. The latter predicted noise equivalent to that from a black body at 10 degrees Kelvin (that is, 10 degrees above absolute zero, measured on the centigrade scale).

The residual noise observed by those at Bell was 3.5 degrees, which was considered quite close to the prediction. Dr. Dicke and his colleagues went to Holmdel to inspect the array and apparently went away convinced.

They themselves have built an antenna to observe on a three-centimeter wavelength and expect to begin observations with it shortly.

### Could Support Theory

If the effect is detected on that wavelength, too, the chances will be greatly increased that the primordial fireball has, in fact, been detected. It may also be easier to assess whether the universe is "open," expanding into infinite space, or "closed" and oscillating.

The temperature of the fireball is estimated to have been at least 10 billion degrees Kelvin, to begin with. However, the expanding cloud originally was not transparent. Only when it had cooled to about 5,000 degrees did the light begin to move freely through space. The continuing expansion of the universe has further stretched the waves until they appear in the radio part of the spectrum, according to the calculations.

The observations at Holmdel were conducted for an entire year. The horn antenna was always aimed at the zenith, across which marched many regions of the universe.

The only specific direction in which no observations were made was toward the Milky Way—the dense portion of our own galaxy—which is too noisy, in radio waves, to permit a valid assessment of other noise sources.

### Participate in Study

Those at Princeton who have taken part in the study include, in addition to Dr. Dicke, Drs. P. J. E. Peebles, P. G. Roll and D. T. Wilkinson. Because their study has not yet been published, they were reluistant yesterday to discuss it. The same was true of Drs. Penzias and Wilson at Bell Laboratories.

Both groups have submitted papers on the subject to The Astrophysical Journal.

The parallel with the Jansky observations of 1931-33 is striking because he, too, was seeking to track down radio noise. In this case his attention was on static interfering with long-range radio communications, particularly that originating in thunderstorms.

As in the recent observation, he tracked down all the obvious sources and was left with a perplexing residue. At first he suspected it came from the sun, but colleagues then suggested that it might be from a point among the stars. The source proved to be the core of the Milky Way galaxy.

His discovery led others to aim antennas at the sky and the thriving science of radio astronomy was born.

United Press International
**Dr. Allan R. Sandage of Mount Palomar Observatory commented on the quasars.**

The New York Times
Published: May 21, 1965
Copyright © The New York Times

# 1965: Novikov on Zeldovich

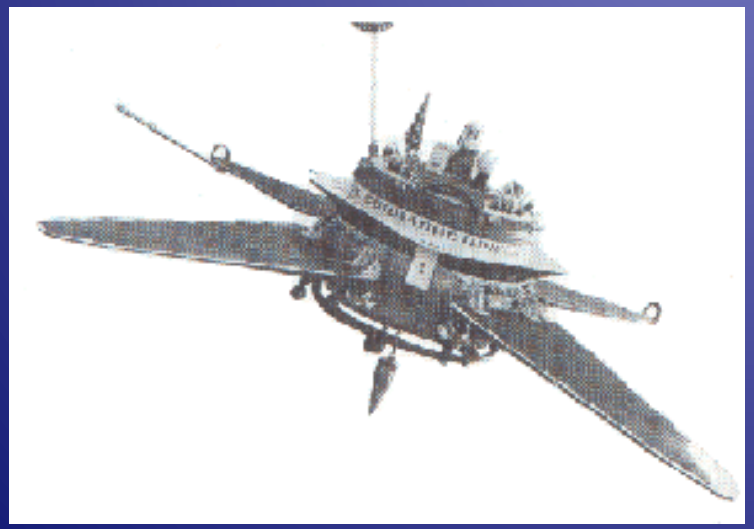
- Novikov reminds Zeldovich of their paper on the detectability of the CMB
- Zeldovich scolds them for not including the spectrum in their paper (which it had)
- Then he “scolded us for the absence of the effective propaganda of our paper”
  - Lesson: You can NEVER please a supervisor like Zeldovich!

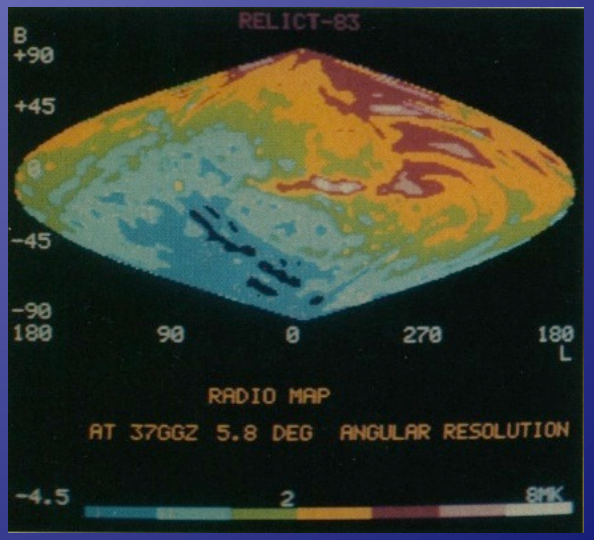
# 1978: Penzias & Wilson

- Nobel Prize in Physics
- Penzias & Wilson acknowledge the D&N ground breaking paper in their Nobel Prize speech
- Mention is made of Alpher, Herman and Gamow in introductory speech

# CMB Dipole & Quadrupole

- Henry 1971 Nature, Vol. 231, p. 516-518
  - First to measure dipole L(true)/L(null) > 200
- First to measure CMB Quadrupole
  - 1981: Wilkinson/Melchiorri ?
  - 1983-4: Prognoz-9/Relikt-1 (USSR) ?





# 1990/1992: COBE

- Jan 1990: Planck BB Spectrum (AAS mtg)
- April 1992: First evidence of (small scale) CMB Anisotropy
  - 2-D map of the early universe shown at APS

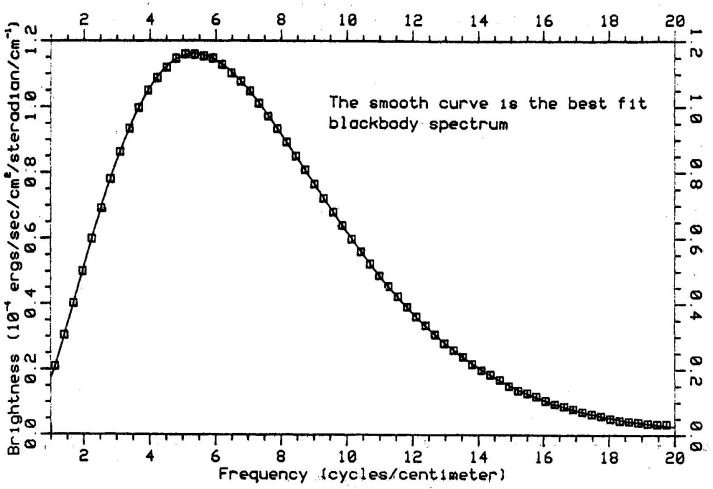
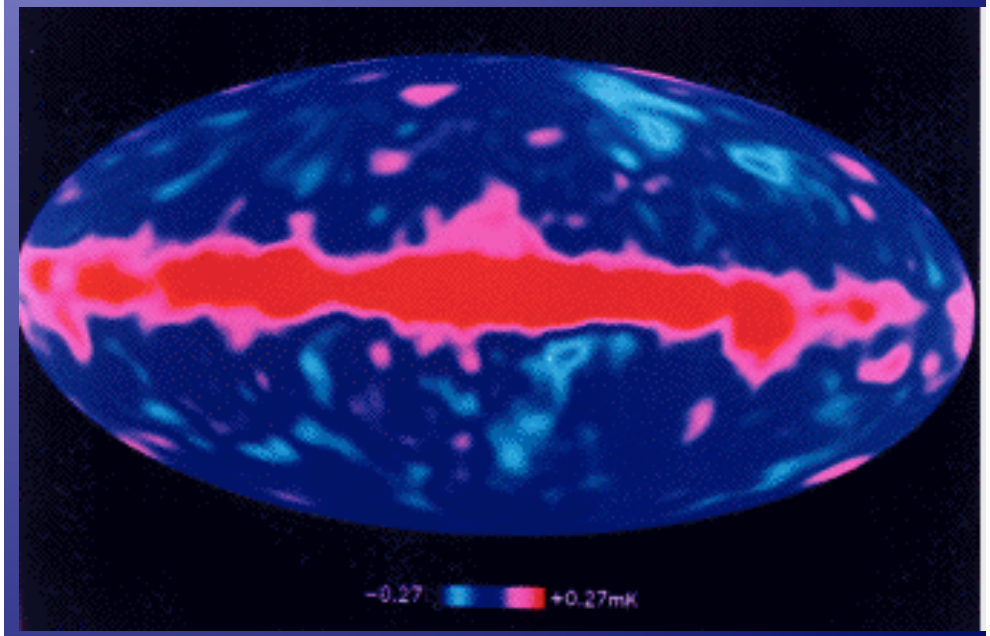
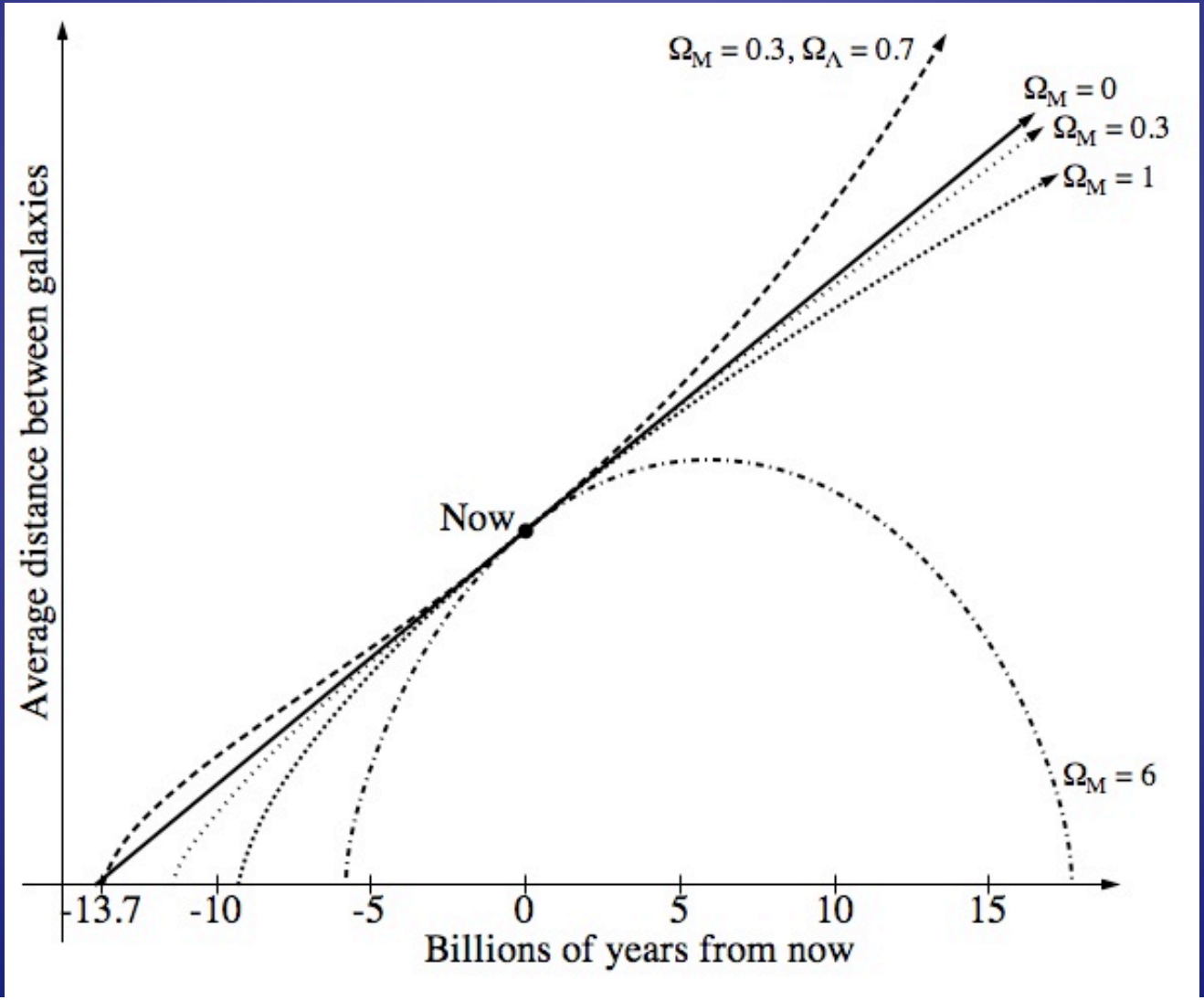



FIG. 9. FIRAS COSMIC MICROWAVE BACKGROUND SPECTRUM.
*Spectrum of the cosmic microwave background radiation, based on nine minutes of FIRAS data. When shown to the American Astronomical Society on January 13, 1990, it brought a standing ovation. Theoretical prediction is solid line, data points are boxes.*

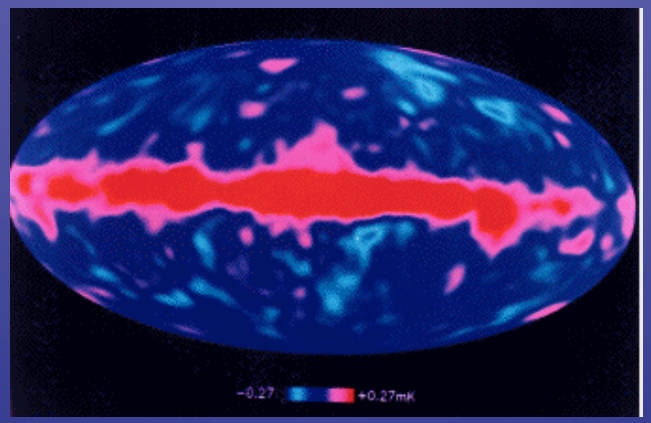


# 1998/1999: Lambda Returns!



# 2006: Mather & Smoot (COBE)

- Mather & Smoot receive the Nobel Prize for COBE CMB discoveries




# A couple of other comments

- Novikov, Doroshkevich, Dicke should also have received the Nobel?
- What about Alpher, Herman, Gamow?

Gott: “Gamow's prediction of the CMB radiation and getting it's temperature right to within a factor of 2 was a remarkable accomplishment -- rather like predicting that a flying saucer 50 ft in width would land on the White House lawn and then watching one 27 ft in width actually show up. One could call it the most remarkable scientific prediction ever to be verified experimentally.”

# A couple of other comments

Hubble gets credit for expansion of The Universe and should not?

"The discovery of the expansion of the universe carried out by Edwin Hubble in 1929 allowed for non-static models of universe that accounted for the observed expansion (the models of Friedmann-Lemaitre that make use of the Robertson-Walker metric)."

From Martinez & Trimble 2009, arXiv:0904.1126v1

# A few of the references used herein:


Kant: http://records.viu.ca/~johnstoi/kant/kant2e.htm

Wright: http://www.astro.ucla.edu/~wright/CMB-dipole-history.html

Kragh & Smith 2003, Hist. Sci., xli

Partridge 2002, Moriond 2002 “Pre-History of CMB Studies”
http://moriond.in2p3.fr/J02/Talks2002/B.Partridge/LesArcs.ps

Gamow: http://books.google.com/books?id=5awirwgmvAoC

Gott: http://books.google.com/books?id=MME33bSTCDsC

Tolman: http://books.google.com/books?id=1ZOgD9qlWtsC

Kragh: Cosmology & Controversy (1996)

Duerbeck & Seitter: In Hubble’s Shadow

Duerbeck & Seitter: Carl Wilhelm Wirtz - Pioneer in Cosmic Dimensions

Mather & Boslough: The Very First Light

Peebles, Page & Partridge: Finding the Big Bang (2009)

Kenneth Glynn Jones “The Search for the Nebulae I-IX” (1967-69)

Friedman & Lemaitre “made the universe expand”, and Alpher and Herman made it glow.

– D.E. Neuenschwander, (Radiations Spring 2009)

“God made two mistakes: he started the universe with a Big Bang, and then he left the 3-degree radiation behind as evidence” – Paul Erdös

# This Talk:

http://astrophysics.arc.nasa.gov/~mway/Hunter.pdf

http://www.giss.nasa.gov/staff/mway/Hunter.pdf